The Formation and Evolution of Planetary Systems: SIRTF Legacy Science in the VLT Era

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Abstract. We will utilize the sensitivity of SIRTF through the Legacy Science Program to carry out spectrophotometric observations of solar-type stars aimed at (1) defining the timescales over which terrestrial and gas giant planets are built, from measurements diagnostic of dust/gas masses and radial distributions; and (2) establishing the diversity of planetary architectures and the frequency of planetesimal collisions as a function of time through observations of circumstellar debris disks. Together, these observations will provide an astronomical context for understanding whether our solar system – and its habitable planet – is a common or a rare circumstance.

Achieving our science goals requires measuring precise spectral energy distributions for a statistically robust sample capable of revealing evolutionary trends and the diversity of system outcomes. Our targets have been selected from two carefully assembled databases of solar-like stars: (1) a sample located within 50 pc of the Sun spanning an age range from 100-3000 Myr for which a rich set of ancillary measurements (e.g. metallicity, stellar activity, kinematics) are available; and (2) a selection located between 15 and 180 pc and spanning ages from 3 to 100 Myr. For stars at these distances SIRTF is capable of detecting stellar photospheres with SNR >30 at $\lambda \leq 24\mu$m for our entire sample, as well as achieving SNR >5 at the photospheric limit for over 50% of our sample at $\lambda = 70\mu$m. Thus we will provide a *complete* census of stars with excess emission down to the level produced by the dust in our present-day solar system.

SIRTF observations obtained as part of this program will provide a rich Legacy for follow–up observations utilizing a variety of facilities including the VLT. More information concerning our program can be found at `http://gould.as.arizona.edu/feps`.

1 Introduction

The **S**pace **I**nfra**R**ed **T**elescope **F**acility (SIRTF) is a key element of NASA's *Origins* program [20] . The 85 cm cryogenic space telescope will be launched into an earth–trailing orbit in 2002. There are three science instruments on–board: IRAC, IRS, and MIPS which will provide imaging and spectroscopy from 3.6–160 μm for an estimated mission lifetime of $\sim$ 5 yrs. The *SIRTF Legacy Science Program* was established to provide access to large coherent datasets as rapidly as possible in support of general observer (GO) proposals. In addition to the program described here there are complementary programs to survey nearby star–forming (Evans et al.), the inner galactic plane (Churchwell et al.), star–formation in nearby galaxies (Kennicutt et al.), a wide–field extragalactic survey (Lonsdale et al.), and a deep pointed survey (Dickinson et al.). For more information concerning the SIRTF Legacy Science Program please visit `http://sirtf.caltech.edu`.

Our modern understanding of the ubiquity of dust disks associated with young stars began with the revelations provided by SIRTF's ancestor IRAS [15]. Later, ISO produced a more complete census of optically–thick disks within 200 pc and revealed the rich dust mineralogy and gas content of these disks (see [13] for review). Understanding the evolution of young circumstellar dust and gas disks as they transition through the planet–building phase requires the $\times$100 enhancement in sensitivity and increased photometric accuracy offered by SIRTF at far-infrared wavlengths. Concerning dust surrounding main sequence stars, IRAS discovered the prototypical debris disks [1] and ISO made additional limited-sample surveys [6]. Neither IRAS nor ISO were sensitive enough to detect dust in solar systems older than a few hundred Myr for any but the nearest tens of stars. SIRTF will detect orders of magnitude smaller dust masses, down to below the mass in small grains inferred for our own present-day Kuiper Belt (6×10^{22} g) surrounding a solar–type star at 30 pc!

We will probe circumstellar dust properties around a representative sample of primordial disks (dominated by ISM grains in the process of agglomerating into planetesimals) and debris disks (dominated by collisionally generated dust) over the full range of dust disk optical–depths diagnostic of the major phases of planet system formation and evolution. Our Legacy program is designed to complement those of Guaranteed Time Observers (GTOs) such that a direct link between disks commonly found surrounding pre–main sequence stars < 3.0 Myr old and our 4.56 Gyr old solar system can be made. Together, these data will help guide studies of the formation and evolution of planetary systems undertaken with facilities such as the VLT.

2 Science Strategy

We take advantage of the efficacy of infrared observations in revealing evidence for planetary systems embedded in dust distributions. In three coordinated modules we will: 1) conduct a survey of post–accretion circumstellar dust disks in

order to understand evolution of disk properties (mass and radial structure) and dust properties (size and composition) during the main phase of planet–building and early solar system evolution for 150 F–G–K stars aged 3–100 Myr; 2) conduct a sensitive search for warm molecular hydrogen in a sub–sample of 50 targets from our dust disk survey, to constrain directly the time available for embryonic planets to accrete gas envelopes; and 3) trace for 150 F–G–K stars aged 100 Myr to 3 Gyr the evolution of dust disks generated through collisions of planetesimals and thereby infer the locations and masses of giant planets through their action on the remnant disk.

Understanding gas–dust dynamics is crucial to our ability to derive timescales important in planet formation and evolution. Modules (1) and (2) have an important synergy in furthering this understanding because dust dynamics are controlled by gas drag rather than radiation pressure when the gas-to-dust mass ratio is >10, while it is the presence of dust that mediates gas heating (and therefore detectability). Module (3) investigates epochs of terrestrial and ice-giant (Uranus- and Neptune-like) planet formation and the subsequent dynamical evolution of planetary systems. Our combined program will help place the formation and evolution of our own solar system in context, by providing the first estimates of the diversity of planetary architectures over the full range of radii relevant for planet formation. Our large sample will enable us to measure the *mean properties* of evolving dust disks, discover the *dispersion* in evolutionary timescales, and provide a database against which future studies can measure how various evolutionary paths might be *related to stellar properties*.

2.1 Formation of Planetary Embryos

Our experiment begins as the disks are making the transition from optically thick to thin, the point at which all of the disk's mass first becomes detectable through direct observation [17]. The goals are to: 1) constrain the initial structure and composition of $\tau < 1$ post-accretion disks; 2) measure changes in the dust particle size distribution due to coagulation of interstellar grains and shattering associated with high-speed planetesimal collisions; 3) characterize the timescales over which primordial disks dissipate and debris disks arise; and 4) infer the presence of newly formed planets at orbital radii of 0.3-30 AU.

Photometric observations from 3.6-160μm probe temperatures (radii) encompassing the entire system of planets in our solar system [2]. Detailed spectrophotometry from 5.3–40 μm will permit a search for gaps in disks caused by the dynamical interaction of young gas giant planets and the particulate disk from 0.2–10 AU [3]. Mid–infrared spectroscopic observations are sensitive to dust properties including size distribution and composition which in turn probe the physical conditions in the disk [7]. We will determine, for example, the relative importance of broad features attributed to amorphous silicates (ubiquitous in the ISM) compared to numerous narrow features throughout the 5.3–40 μm region due to crystalline dust (observed only in circumstellar environments [12]). In this way, we can diagnose radial mixing in the disk because the temperature

required to anneal grains (> 1500K) is substantial higher than the inferred temperature of the emitting material (~ 300K). Further, the shape and strength of spectroscopic features can provide constraints on the fractional contribution of each grain population to the total opacity; a necessary ingredient to estimate dust mass surface densities.

2.2 Growth of Gas Giants

We will undertake the most comprehensive survey to date of H_2 gas in post–accretion disk systems in order to characterize its dissipation and to place limits on the time available for giant planet formation. We plan to survey 50 stars selected from our dust disk survey sample at high spectral resolution (R=600) from 10–37 μm, including both the S(0) 28 μm and S(1) 17 μm H_2 lines. We focus on the post-accretion epochs from 3–100 Myr to examine whether gas disks do indeed persist after disk accretion onto the star has ceased [19] and planetesimal agglomeration has provided "nucleation sites" for gas giant planet formation [8]. We estimate that if the gas and dust temperatures are within 40K and both are optically thin, the dust emissivity in the continuum can be suppressed enough to enable gas detection while maintaining the gas temperature via collisions. We expect to be sensitive to $>2 \times 10^{-4}$ $M_\odot[H_2]$ at 70–200 K.

2.3 Mature Solar System Evolution

We complement our investigation of the initial decay of both dust and gas signatures in first generation "primordial" disks with a comprehensive study of second generation "debris disks". The presence of *any* observable circumstellar dust around stars older than the maximum lifetime of a primordial dust disk (the sum of the to–be–determined gas dissipation timescale and the characteristic Poynting–Robertson drag timescale) provides compelling evidence not only for large reservoirs of planetesimals colliding to produce the dust, but also for the existence of massive planetary bodies that dynamically perturb planetesimal orbits inducing frequent collisions [10].

We will undertake the first comprehensive survey of solar-type stars with ages 100 Myr to 3 Gyr sensitive to dust disks comparable to that characteristic of our own solar system throughout its evolution from 100–300 Myr (the last phase of terrestrial and ice giant planet–building in our solar system) through 0.3–1 Gyr (bracketing the "late heavy bombardment" impact peak in our own solar system) and finally to 1.0–3.0 Gyr (examining the diversity of evolutionary paths from early activity to mature planetary system). Spectroscopic observations from 5.3–40 μm enable diagnosis of gaps caused by giant planets [9] and estimates of dust size and composition which translate directly into constraints on the mass opacity coeffients for the dust [14] as well as Poynting-Robertson drag timescales [1].

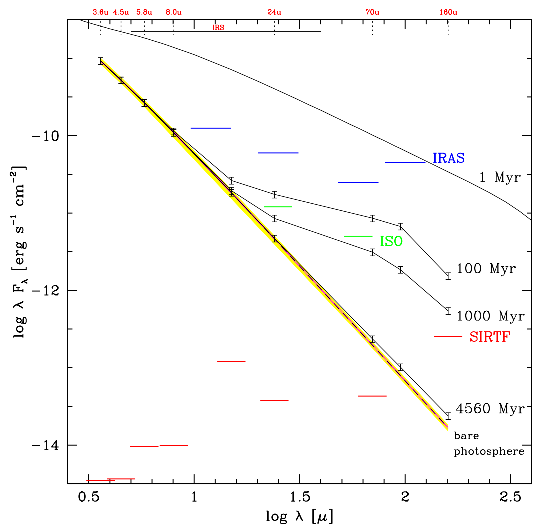

Fig. 1. Model SED for a hypothetical solar system based on a G2V stellar photosphere at 30 pc, asteroid belt zodiacal dust, and Kuiper belt dust for ages 4560, 1000, and 100 Myr along with an optically thick disk SED characteristic of <1-2 Myr old stars. Also shown are the IRAS, ISO, and SIRTF sensitivity limits. IRAS detected optically thick disks out to 160 pc. At 30 pc, ISO would have detected this young solar system at ages of a few hundred Myr while SIRTF will detect it at ages as old as the Sun.

3 Observing Strategy

3.1 Sample Characteristics

To derive statistically meaningful results on the dust properties, we will observe ∼50 stars in each of 6 logarithmically spaced age bins from 3 Myr (connecting our Legacy program to that of Evans et al.) to 3 Gyr (beyond which there is strong emphasis by GTO's). Our targets span a narrow mass range (0.8-1.2 $M_\odot$) and are proximate enough to enable a complete census for circumstellar dust comparable to our model solar system as a function of age ([11]; [16]). We will measure the stellar photosphere at SNR>30 for $\lambda \leq 8\mu$m at ages < 100 Myr, and SNR>20 for $\lambda \leq 70\mu$m at ages > 100 Myr (subject to calibration uncertainties). To identify gaps in the dust distribution created by the presence of giant planets from 0.2–10 AU, we require relative spectrophotometry with SNR>30 from 5.3–40 μm.

For the gas evolution module, we have chosen 10 stars for first-look observations with the high resolution mode of the IRS. This sample spans a range of spectral type (F3–K5), age (3–100 Myr), L_x/L_{bol} ratios $(10^{-3} - 10^{-5})$. Because the line-to-continuum ratio starts to limit our detectable H_2 line flux at R=600 when the continuum at 20μm is >100 mJy these sources are chosen to have optically–thin mid–infrared excess emission on the basis of IRAS and ISO

observations. These observations will enable us to explore the limits implied by null results and guide our choice of follow–up observations for 40 more stars drawn from our dust disk survey. Our goal is a quantitative limit on the lifetime of gas–rich disks capable of forming giant planets.

Table 1. Proposed SIRTF Observations

Instr.	**# stars**	**Total Time inc. overhead**	**SNR on Photosphere**	**Objectives**
IRAC	300	40 hrs		3.6, 4.5, 5.8 and 8.0 μm photometry.
		[419s/star]	>30 all bands	**Measure photosphere** and hot dust excess.
MIPS	300	135 hrs		24, 70, and 160 μm phot.
		[1100-1900s/star]	>30 at 24μm >5 at 70μm	**Complete census** for dust at 24 μm and most of sample at 70 μm.
IRS (Lo)	300	125 hrs		R $\sim$ 60-120 spectra.
		[740-2020s/star]	>30 at 5.3-14.2μm >10 at 14.2-40μm	**Detailed SED** and spectral analysis.
IRS (High)	50	50 hrs [720-5180s/star]	>3 to detect 2 $\times 10^{-4}$ $M_\odot$ of H_2	R $\sim$ 600 spectra 10-37μm. **Measure H_2 gas mass** & resolve dust features.
SUM		**350 hrs**		

3.2 SIRTF Data

The SIRTF data, in conjunction with the ancillary observations described below, will be used to: (1) establish the contribution of the stellar photosphere to the observed spectral energy distribution; (2) measure any excess infrared emission from estimates of the opacity of the dust as a function of wavelength; and (3) determine the amount, distribution, and composition of the circumstellar material through mid–infrared spectroscopy. Our goal is to collect data capable of realizing the fundamental limits imposed by instrument stability and systematic calibration uncertainties. Integration times are chosen according to each star's distance, age and spectral type to reach uniform SNR at the photospheric limits. Table 1 summarizes the observations, their most basic objectives, and the total amount of observing time requested including all overheads.

3.3 Ancillary Data

While SIRTF observations alone are an extremely valuable dataset, the scientific impact of our program will be enhanced when these data are combined with those

at shorter and longer wavelengths. The ancillary data that will be assembled and provided to the community for each star in our sample is summarized in Table 3. We will search for dust located at large radii and too cold to radiate strongly in the MIPS 160 μm band by obtaining sub–mm continuum observations for every source in our sample. These observations will provide us with measurements of (or constraints on, in the case of nondetections) the spectral slope ($F_\nu \sim \nu^{-\alpha}$) which can be used to constrain particle size distributions. We also plan a limited campaign of 5 μm, 10 μm and 20 μm imaging using the MMT, Keck, Magellan, and the VLT for the brightest objects in our sample. Intermediate–band photometry in carefully chosen atmospheric windows (e.g. 5.3 and 11.7 μm) will provide a useful check on the SIRTF calibration when tied to the same photometric standards of Cohen et al. [5].

Table 2. Ancillary Data

Instrument	**# stars**	**Observing Time**	**Objective**
Tycho/Hipparcos	300	Public	Proper Motions
Tycho/Hipparcos	300	Public	B_T, V_T, and H_p photometry
2MASS	300	Public	J, H, K_S photometry
Optical Spectrographs	300	In hand	Spectral classification
Mid-Infrared Imagers	30	4 runs	5-25μm imaging photometry
SMT/CSO/SEST	300	17 weeks	sub–mm photometry

4 The Legacy

The combined SIRTF + Ancillary Data catalog along with specific tools for reduction, calibration, and interpretation of data will create a rich Legacy in science and in services provided to the community.

First, we will construct 3.6-160μm + sub–mm spectral energy distributions for a representative sample of ~300 F-G-K stars aged 3 Myr - 3 Gyr within 15-160 pc of the Sun, providing a complete set of ancillary data characterizing the properties of the stars.

Second, we will combine these data with model calculations to discern the timescales for gas giant and terrestrial planet formation in circumstellar disks, and the evolution of these systems on Myr to Gyr timescales.

Third, we will provide a database of targets for follow–up with SIRTF and other platforms. Our results will support GO programs with similar scientific aims and help in selecting samples (by age, mass, metallicity, etc.) for additional work. Follow-up with MIPS in SED mode and with IRS at high spectral resolution are areas in which GO's can directly exploit the Legacy database. Our SIRTF+Ancillary results will also have a strong impact on future space–based infrared surveys, as well as programs enabled by new ground-based facilities

such as those soon available on the VLT. Follow–up observations with VISIR are capable of directly resolving the thermal disk emission from 10–20 μm [18]. Further, high velocity resolution spectroscopic observations could resolve the line profiles of warm circumstellar gas indicating its radius of origin in a Keplerian disk [4]. Additional studies utilizing ISAAC, CONICA, and VLTI with MIDI will yield further insights.

Fourth, due to the nature of our program (large sample of uniform observations) we hope to assist the SIRTF Science Center and instrument teams in improving the photometric accuracy of SIRTF from the initial projections of 20% to target values of 5 % for the benefit of the entire astronomical community.

Fifth, a second fundamental data product of this Legacy project derives from the serendipitous discoveries made as part of our primary survey. Our program involves observing ∼300 fields with 38”×38” field of view to the limiting sensitivity of SIRTF at 3.6, 4.5, 5.8, & 8 μm and these same ∼300 field centers with 5’×5’ field of view at 24, 70 & 160 μm, over galactic latitudes ranging from $b = 20°$ to $b = 90°$.

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